

Photon + jets at DØ

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Photon plus jet production has been studied by the DØ experiment in Run II of the Fermilab Tevatron Collider at a centre of mass energy of $\sqrt{s} = 1.96$ TeV. Measurements of the inclusive photon, inclusive photon plus jet, photon plus heavy flavour jet cross sections and double parton interactions in photon plus three jet events are presented. They are based on integrated luminosities between 0.4 fb^{-1} and 1.0 fb^{-1} . The results are compared to perturbative QCD calculations in various approximations.

1 Introduction

Photons originating from the hard subprocess and produced during fragmentation contribute to photon cross sections in hadron-hadron collisions. The contribution of fragmentation photons can be significantly reduced by isolation requirements. Thus, isolated photon cross sections are sensitive to the dynamics of the hard subprocess, to the strong coupling constant α_s and to the parton distribution functions (PDF's) of the colliding hadrons. In the following isolated photon and photon plus jet cross section measurements from the DØ experiment are presented [1] as well as a measurement of double parton interactions in photon plus three jet events.

2 Inclusive photon cross section

DØ has measured the inclusive photon cross section [2] based on an integrated luminosity of 380 pb^{-1} . Photon candidates are defined as clusters of electromagnetic (EM) calorimeter cells within a cone of radius $R = 0.2$ in the space of pseudorapidity η and azimuthal angle ϕ , if more than 95% of the detected energy is located in the EM layers of the calorimeter and

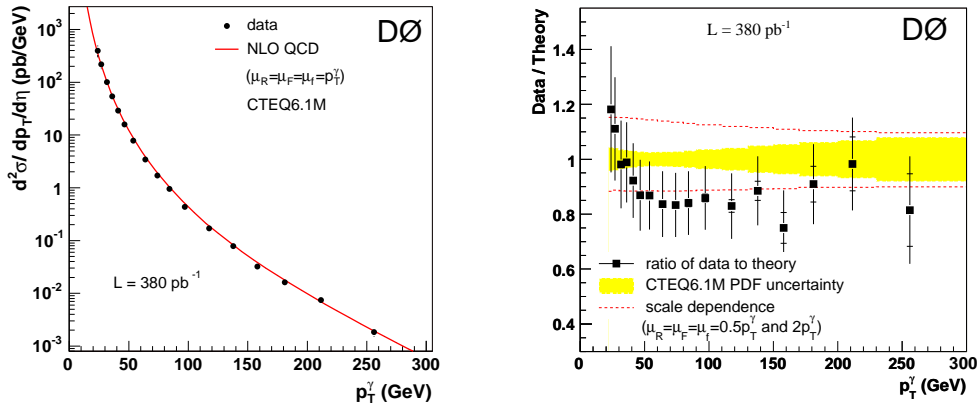


Figure 1: Double differential inclusive photon cross section (left) and data over theory ratio (right) in comparison to the prediction of JetPhox.

the probability for a track match is below 0.1%. As isolation criterion the transverse energy not associated to the photon in a cone of radius $R = 0.4$ around the photon direction has to be less than 0.10 times the energy of the photon. Backgrounds from cosmics and electrons from W boson decays are vetoed by a missing transverse energy requirement of $\cancel{E}_T < 0.7p_T^\gamma$. Electromagnetic cluster and track information is fed into a neural network (NN) to increase the photon purity further. Central photons ($|\eta| < 0.9$) with a transverse momentum above 23 GeV are selected. The differential cross section is compared to the NLO prediction of JetPhox [3][4][5] in Fig. 1. The results are still consistent with theory but a shape similar to previous observations of UA2 and CDF emerges.

3 Photon plus jet cross section

The inclusive photon plus jet cross section [7] has been measured by DØ based on an integrated luminosity of 1.0 fb^{-1} . Photon candidates have to deposit at least 96% of the detected energy in the EM layers of the calorimeter. As isolation criterion the transverse energy not associated to the photon in a cone of radius $R = 0.4$ around the photon direction has to be less than 0.07 times the energy of the photon. The missing transverse energy requirement is $\cancel{E}_T < 12.5 \text{ GeV} + 0.36p_T^\gamma$. Electromagnetic cluster and track information is fed into a neural network to increase the photon purity further. Central photons ($|\eta| < 1.0$) with a transverse momentum above 30 GeV are selected. Jets are defined in the energy scheme by the Run II midpoint cone algorithm [6] with a radius of $R = 0.7$. The jets with a transverse momentum above 15 GeV are selected in the central ($|\eta^{\text{jet}}| < 0.8$) or the forward ($1.5 < |\eta^{\text{jet}}| < 2.5$) region. Finally, the photon and the leading hadronic jet have to be separated by $\Delta R(\gamma, \text{jet}) > 0.7$.

The triple differential cross section is measured as a function of transverse photon momentum and jet and photon rapidities in four bins, distinguished by central and forward jets on the one hand and same/opposite side jet photon rapidities on the other hand. These four kinematic intervals probe different momentum phase space regions of the two initial interacting partons. Fig. 2 (left) shows the data versus theory (JetPhox) ratio as a function

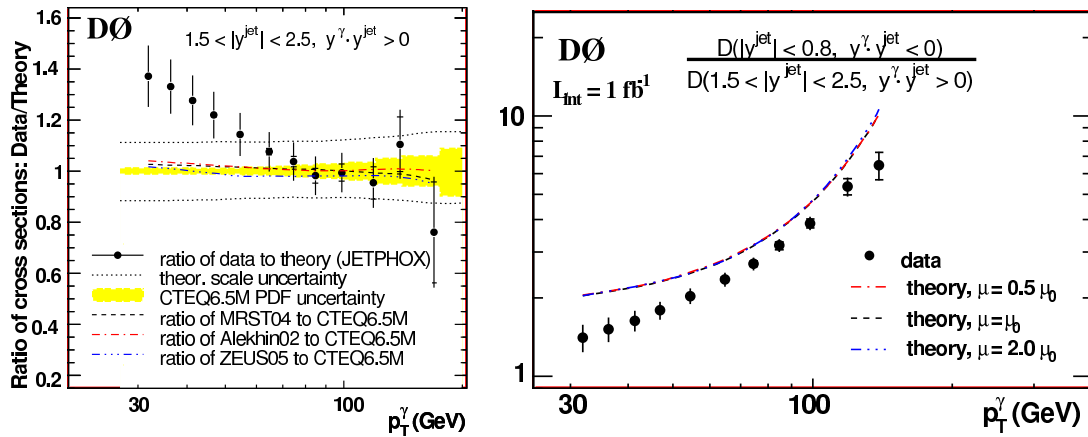


Figure 2: Data over theory ratio and ratio of two photon and jet rapidity bins.

of photon transverse momentum for forward jets and same side photon and jet events. The theory is not able to describe the shape of the data over the whole measured range of photon rapidities. The shape is similar to previous observations of UA2 and CDF. The right plot shows the ratio of the cross section of central jets with opposite side photon rapidities over the cross section of forward jets with same side photon rapidities for both, data and theory. The ratio has the advantage of reduced uncertainties due to correlated errors. The cross section ratio reveals quantitative disagreement between data and theory.

4 Inclusive photon plus heavy flavour jet cross section

DØ has measured the inclusive photon plus heavy flavour jet cross section [8] making use of an integrated luminosity of 1.0 fb^{-1} . One isolated photon with a transverse momentum above 30 GeV has to be found in the rapidity range of $|y_\gamma| < 1.0$. Electromagnetic cluster and track information is fed into a neural network to improve the photon purity. Backgrounds from cosmic and electrons from W boson decays are vetoed by a missing transverse energy requirement of $\cancel{E}_T < 0.7p_T^\gamma$. DØ Run II jets [6] with a cone radius of 0.5 and a transverse momentum above 15 GeV are considered in the central pseudorapidity range of $|y_{\text{jet}}| < 0.8$. The leading momentum jet has to have at least two tracks and a neural network which exploits the longer lifetimes of heavy flavoured hadrons is applied to enhance the heavy flavour jet content of the considered events. Same side and opposite side photon and jet rapidity events are treated separately. The fractional contributions of b and c jets are determined by fitting templates (Fig. 3 left) of a function $P_{\text{HF-jet}} = -\ln \prod_i P_{\text{track}}^i$ to the data, where P_{track}^i is the probability that a track originates from the primary vertex. Jets from b quarks have typically large values of $P_{\text{HF-jet}}$. Fig. 3 (right) shows the data over theory ratio as a function of the photon transverse momentum of the b quark plus photon production

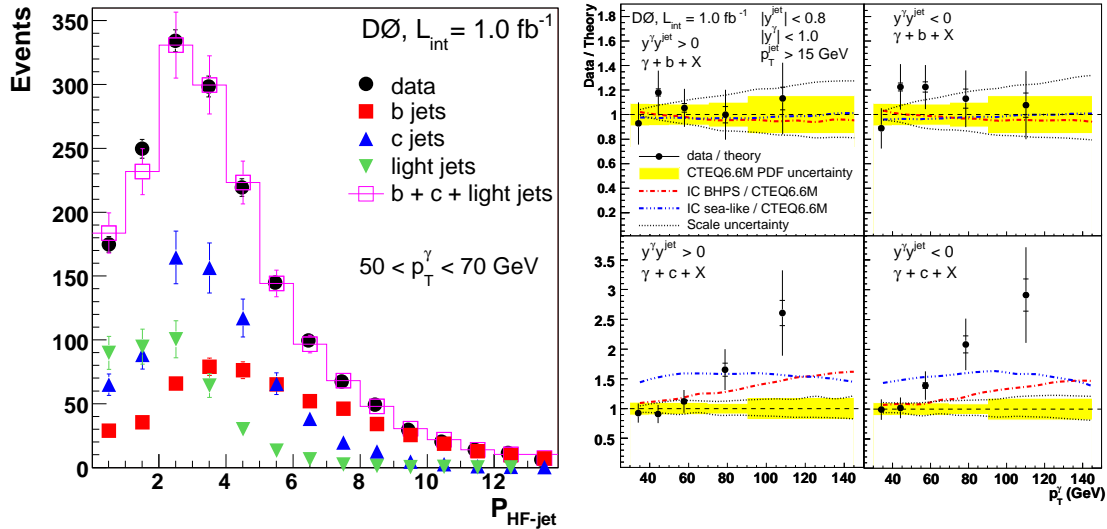


Figure 3: Jet flavour templates and data over theory ratio in comparison to theory.

(top) and c quark plus photon production cross sections in the same side (left) and opposite side (right) photon and jet rapidity bins. The next-to-leading order predictions [9] are based on techniques to calculate the cross section analytically [10]. While the prediction agrees with the measured cross section for b quark plus photon production over the whole range of photon transverse momenta, the prediction underestimates the measured cross section for c quark plus photon production for photon transverse momenta above 70 GeV.

5 Double parton interactions in photon plus three jet events

The double parton scattering in photon plus three jet events has been measured by DØ [11] making use of an integrated luminosity of 1.0 fb^{-1} . This measurement provides complementary information about the proton structure, namely the spatial distribution of partons inside the proton. Possible parton-parton correlations and an impact on the proton parton distribution functions (PDF's) can be investigated. Events with an isolated photon in the transverse momentum range between 60 and 80 GeV, a leading jet with a transverse momentum above 25 GeV and two further jets with a transverse momentum above 15 GeV are selected. The main background arises from single parton scattering events with additional jets from initial and final state radiation. The cross section for double parton scattering can be expressed as $\sigma_{\text{DP}} = m\sigma_A \frac{\sigma_B}{2\sigma_{\text{eff}}}$, where $\sigma_{A,B}$ are the cross sections of the process A and B. σ_{eff} characterises the size of the effective interaction region and the term $\sigma_B/2\sigma_{\text{eff}}$ gives the probability of a second interaction B, given that a first interaction A has already taken place. In this analysis the permutation factor m equals to two since the processes A and B can be distinguished due to the photon. The measurement is done in three transverse momentum bins of the second jet from 15 to 20, 20 to 25 and 25 to 30 GeV using data driven techniques based on the different transverse momentum spectra between jets of dijet events and those of single parton scattering events with jet radiation. The discriminating

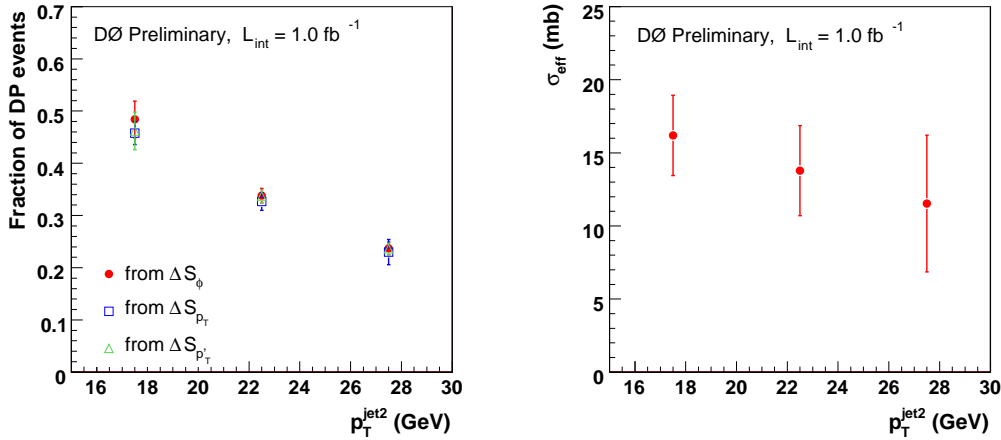


Figure 4: Fraction of double parton events (left) and σ_{eff} (right) as a function of the second transverse momentum jet.

variables $S_\phi = \frac{1}{\sqrt{2}} \sqrt{\left(\frac{\Delta\phi(\gamma,i)}{\delta\phi(\gamma,i)}\right)^2 + \left(\frac{\Delta\phi(j,k)}{\delta\phi(j,k)}\right)^2}$, $S_{p_T} = \frac{1}{\sqrt{2}} \sqrt{\left(\frac{|\vec{P}_T(\gamma,i)|}{\delta P_T(\gamma,i)}\right)^2 + \left(\frac{|\vec{P}_T(j,k)|}{\delta P_T(j,k)}\right)^2}$ and $S_{p'_T} = \frac{1}{\sqrt{2}} \sqrt{\left(\frac{|\vec{P}_T(\gamma,i)|}{|\vec{P}_T^\gamma|+|\vec{P}_T^i|}\right)^2 + \left(\frac{|\vec{P}_T(j,k)|}{|\vec{P}_T^j|+|\vec{P}_T^k|}\right)^2}$ are constructed, where each object can be either the photon or one of the three jets. Essentially the variables correspond to the quadratic sum of the object pair azimuthal angle difference significances, the object pair transverse momentum significances and the object pair transverse momentum vectors over scalar sum, respectively. Finally the observable $\Delta S = \Delta\phi(p_T^{\gamma, \text{jet}_i}, p_T^{\text{jet}_j, \text{jet}_k})$ is computed for the object pair combination which minimises S . The distributions of the distinguishing ΔS variables are compared to two sets of photon plus three jet data with one vertex events which differ in signal fractions. As it turned out single parton scattering events are mostly ($\gtrsim 90\%$) concentrated in the region $\Delta S > 2.0$. Fig. 4 (left) shows the fraction of measured double parton scattering events which is decreasing with increasing second jet transverse momentum. The right plot shows the measured effective cross section σ_{eff} . The measurements in the different second jet transverse momentum bins are consistent with each other within errors and an average effective cross section $\langle \sigma_{\text{eff}} \rangle = 15.1 \pm 1.9$ mb is obtained. This value is consistent with previous measurements of UA2 and CDF.

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